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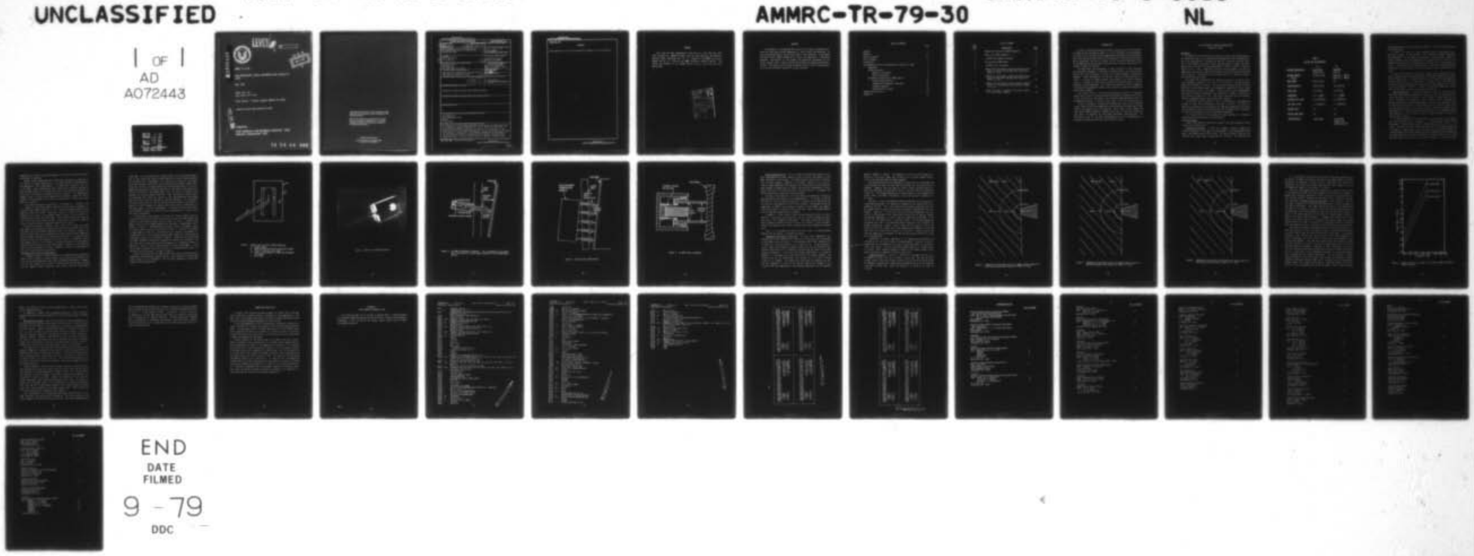

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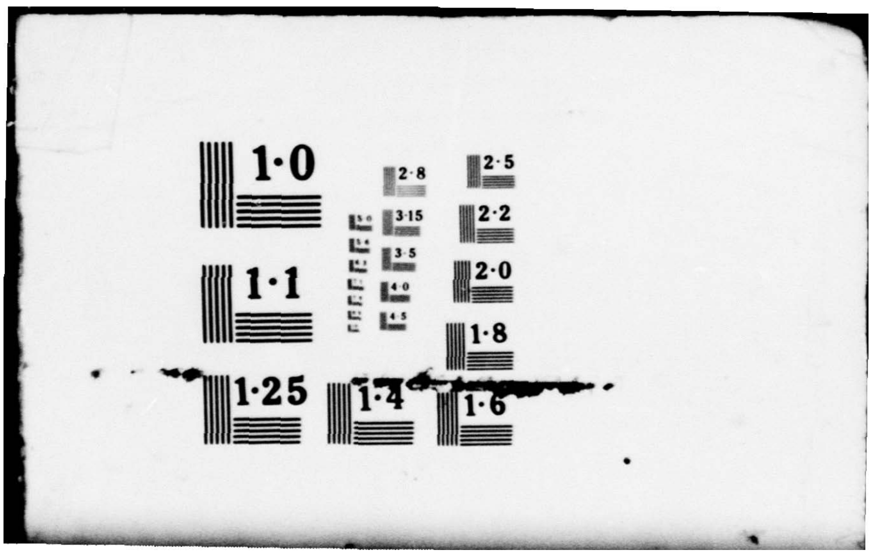
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AMMRC TR 79-30

HIGH-TEMPERATURE STRAIN INSTRUMENTATION FEASIBILITY STUDY

MAY, 1979

TERRA TEK, INC.
SALT LAKE CITY, UTAH

FINAL REPORT - CONTRACT NUMBER DAAG46-78-C-0033

Approved for public release; distribution unlimited.

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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The problem of instrumenting the strain in all three coordinate directions on a body whose surface temperature is 1100 to 1650°C was addressed. No pre-existing satisfactory solution was found in the literature. A new needle and pivot point (NAPP) mechanism for strain instrumentation is therefore proposed. Calculations of the thermal and mechanical performance of the device indicate that it should satisfy the desired instrumentation characteristices. The device could be used to measure triaxial strains

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ABSTRACT

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FORWARD

This study has been conducted by Terra Tek Inc., Salt Lake City, Utah under Contract No. DAAG46-78-C-0033 from the Army Materials and Mechanics Reserach Center, Watertown, MA. Mr. J. F. Dignam of the AMMRC was project manager and Dr. S. C. Chou of the AMMRC served as technical monitor. The advice and guidance of Mr. Dignam and Dr. Chou in this study are much appreciated.

ABSTRACT

The problem of instrumenting the strain in all three coordinate directions on a body whose surface temperature is 1100 to 1650°C was addressed. No pre-existing satisfactory solution was found in the literuature. A new needle and pivot point (NAPP) mechanism for strain instrumentation is therefore proposed. Calculations of the thermal and mechanical performance of the device indicate that it should satisfy the desired instrumentation characteristices. The device could be used to measure triaxial strains simultaneously at 40 or more different locations on a test structure.

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INTRODUCTION

In order to design aerospace and defense structures which are economical in weight and yet structurally sound, it is often necessary to perform mechanical tests at the elevated service temperature anticipated for the structure. Such tests should be made initially on the materials from which the structure may be fabricated, and finally, certain critical structural components should be instrumented and tested under conditions which simulate the service environment as nearly as possible.

The application and measurement of loads (stresses) on both laboratory and structural specimens is relatively straight-forward, for the most part, because the load transducers can easily be located remotely from the hot specimen. Strain measurements, on the other hand, have been much more difficult. In order to properly analyze the response of an actual structure (such as a frustum of a cone used in a missile) to applied loads at high temperature, strain measurements in all three coordinate directions are needed at a relatively large number of points on the structure surface whose temperature may be 1100 to 1650°C.

The initial effort of the contract therefore consisted of a literature search and a survey of existing measuring techniques to determine which ones, if any, could fulfill the needs of the projected high-temperature strain instrumentation problem. A review of the survey is given in the next section.

Since no acceptable instrumentation method was found in the literature survey, ideas for new high-temperature strain-measuring techniques were formulated in an attempt to solve the problem. One of these, using a Needle And Pivot Point (NAPP) mechanism, appeared promising, and hence was studied in some detail to determine its calculated performance characteristics. The feasibility study of the NAPP high-temperature strain instrumentation is discussed following the review of the literature survey.

HIGH-TEMPERATURE STRAIN INSTRUMENTATION FEASIBILTIY STUDY

Background:

The objective of the feasibility study was to define the optimum approach for measuring strains in two different high-temperature test configurations. The first configuration of interest was that of a laboratory specimen, probably of the standard "dog-bone" tensile specimen design, in which resistance heating would be used to achieve temperatures of 1100 to 1650°C in times of about 1.5 sec or less. Immediately following the attainment of the desired temperature, the specimen might be subjected to a dynamic test which may last only a few msec. Longitudinal strain resolutions of 0.1 percent or better were desired during the test.

The second test configuration of interest consisted of an actual structural component, probably in the form of a frustum of a cone which may be about 300 mm diameter at the base. The cone would be heated rapidly to 1100 to 1650°C by a surrounding furnace, and subsequently subjected to various loads approximating the service environment. Biaxial surface strain measurements plus radial deflection measurements were desired at a number of locations on the structure, perhaps 40 in all. Good strain resolution and rapid response times to accommodate dynamic testing were again required.

The desired specificiations of the strain-measuring instrumentation systems for both test configurations are shown in Table I. Of course, it would be an advantage to use basically the same high-temperature strain-measuring concept for both test configurations, but unrelated strain transducers for the two configurations were also considered acceptable.

The initial effort of the feasibility study centered on a literature survey of existing techniques as described below.

Literature Survey:

Some of the references studied with regard to the high-temperature strain problem are discussed below.

Nonoptical Techniques: In 1973, M. M. Lemcoe of Batelle Columbus Laboratories prepared a final report on "Development of High Temperature Strain Gages" under NASA Contract NAS 1-11277. The report concerns electrical resistance strain gages good to about 820°C for one hour. The relatively low

TABLE I

STRAIN GAGE REQUIREMENTS

	(1)	(2)
SPECIMEN CONFIGURATION	LAB SPECIMEN (ROUND OR FLAT)	STRUCTURES (FRUSTA)
SPECIMEN DIAMETER (WIDTH)	2.5 MM TO 50 MM	MINOR O.D. = 200 MM MAJOR O.D. = 300 MM
GAGE LENGTHS	25 MM TO 50 MM	N/A
STRAIN RESOLUTION	.001 OR BETTER	.001 OR BETTER
STRAIN RATES	UP TO 10/SEC	UP TO 10/SEC
TEMPERATURES	R.T. TO 1650°C	R.T. TO 1650°C
SPECIMEN HEAT-UP RATE	UP TO 1100°C/SEC	UP TO 200°C/SEC
SOAK TIME AT TEMP	0 TO INDEFINITE	0 TO INDEFINITE
MAXIMUM STRAIN	0.1	0.1
MULTIPLE GAGE POINTS	NO	YES
STRAIN DIRECTION	LONGITUDINAL	LONGITUDINAL, LATERAL, PLUS RADIAL DEFLECTION

maximum temperature of the technique discourages its use for the problem under consideration here.

In 1969 C. H. Wells of Pratt & Whitney Aircraft, Middletown, Conn., published a paper in ASTM STP 465, p. 87, entitled "Elevated Temperature Testing Method". In the paper he describes a strain-measuring system involving aluminum oxide rods attached to the gage points of a tensile test specimen such that an LVDT attached to the other ends of the rods measures the strain. The technique, as presented by Wells, would cause severe temperature disturbances in the specimen for the rapid heating rates considered in this study.

A very similar technique, except for using a variable capacitance transducer in place of the LVDT, was described in ASME Paper 73/WA/PVP-4, "Elastic-Plastic Creep Analysis of Thermal Rachetting in Straight Pipe and Comparisons with Test Results" by J. R. Corum and W. K. Sartory in 1973. The capacitance transducers had the advantage that they would withstand temperatures in excess of those associated with LVDT's. However, the maximum temperature of 600°C cited in the paper is far too low to be of interest here.

Optical Techniques: The optical methods of measuring strain generally have much higher maximum temperature limitations than the nonoptical techniques described in the literature. Quite a number of papers have been written on holographic measurement of strain. However, these techniques are generally restricted to displacements which are very small compared to those of interest here; furthermore, they generally require a degree of stability of the test apparatus which is not easily attained. Finally, holographic strain measurement in all three coordinate directions would be a formidable task at room temperature. For a specimen inside a furnace at 1650°C, it would be a doubtful goal to pursue.

An optical method which may be applicable to the laboratory test specimen case was described by W. N. Sharpe, Jr., "Interferometric Surface Strain Measurement", International Journal of Nondestructive Testing, Vol. 3, p. 59 (1971). He used laser light reflections from two closely spaced indentations to produce a fringe pattern, and the fringe shift during the experiment was sensed photometrically and related to the strain between the two indentations. His gage length was 0.125 mm, his sensitivity was 0.25 percent strain, and he measured dynamic plastic strains as large a 8 percent. He also used square indentations for biaxial strain measurement, but no method of measuring radial displacement is mentioned.

Another optical method applied to laboratory specimens was published by R. H. Marion of Sandia Laboratories in his paper entitled "A New Method of High-Temperature Strain Measurement", in Experimental Mechanics, Vol. 18, p. 134 (1978). Marion cemented two small nodules to the tensile specimen to mark the gage length, and followed the motion of the nodules during the test using laser illumination and commercial optical trackers. This method would probably cause a rather severe temperature disturbance around the nodules cemented to the specimen for the case of interest here, in which very rapid heating is required.

A very similar method was reported by S. G. Babcock, P. A. Hockstein, and L. J. Jacobs of the General Motors Materials and Structures Laboratory in Technical Report SAMSO TR 69-393, Vol. II, "High Heating Rate Response of Two Materials from 72°F to 6000°F", dated 1970. However, instead of using nodules cemented to the sides of the specimen, Babcock, et.al., used Ta and Hf reflecting bands to mark the gage length. They found that successful application of the reflecting bands required a complicated high-vacuum sputtering process using ultra-clean surfaces and high-purity Hf and Ta.

The optical methods of Babcock, et.al., and of W. N. Sharpe, Jr., would both appear to be acceptable candiates for measuring the desired strains for the case of the rapidly-heated laboratory tensile test specimen. However, any optical system other than holography would become infeasible when expanded to the simultaneous measurment of as many as 40 locations on a single structure because of the cost and complexity of the test set-up. Furthermore, none of the methods found in the literature, including holography, was designed to measure biaxial strains plus radial displacement. Therefore, it was concluded that a new strain-measuring system is needed to satisfy the requirements of the test on high-temperature structures.

The Needle And Pivot Point (NAPP) Device:

A number of ideas for the desired strain instrumentation were generated, some of which required a compound system, such as optics and ultrasonics, to provide the high-temperature strain and displacement measurements. However, only one idea seemed to come close to satisfying the desired specifications and yet appeared simple, economical, and entirely feasible using present technology. It was reasoned that a ceramic needle could be passed through a hole in the furnace wall and be spring-loaded with its point pressed against the structure to be instrumented. Just outside the furnace wall, the needle would pass through a pivot point which would allow the needle to move freely along its own axis, but would prevent any motion perpendicular to its axis. Beyond the pivot point, therefore, the motion of the shank of the needle would reflect the motion of the needle-point, i.e., the point of interest on the specimen, in all three spatial directions. Thus, the motion of interest would be translated from inside the furnace to the room-temperature environment where the motion could be measured by standard techniques. By differencing the motion measured by any two such devices placed adjacent to each other, a measure of strain between the needle contact points would be obtained, plus two measurements of radial displacement. A suitable array of the devices would therefore provide the desired multiple measurements of biaxial strain and radial displacement.

A particularly simple method of pivoting the ceramic needle and still allowing motion along the needle axis would be to pass the needle through the center of a unidirectional sheet spring, as shown in Figure 1. A model of the Needle And Pivot Point (NAPP) mechanism has been made, a photograph of which appears in Figure 2. The NAPP mechanism might be used to instrument a point on a body inside a furnace as illustrated in Figure 3. In order to instrument a large number of points on a cone structure in a furnace, for example, instrumentation units, each containing several NAPP transducers, could be placed around the structure, as illustrated in Figure 4. Eight such units containing five NAPP transducers each would instrument 40 locations on a structure. The data from such an array would provide 32 measures of longitudinal strain, 40 measures of laterial strain, and 40 measures of radial displacement. A simplified NAPP transducer could also be used for instrumenting the strain in a laboratory tensile specimen, as shown in Figure 5.

Before concluding that the NAPP system could satisfy the desired high-temperature strain-measuring specifications, it was necessary to investigate several aspects of its performance. The four most important of these investigations are described below.

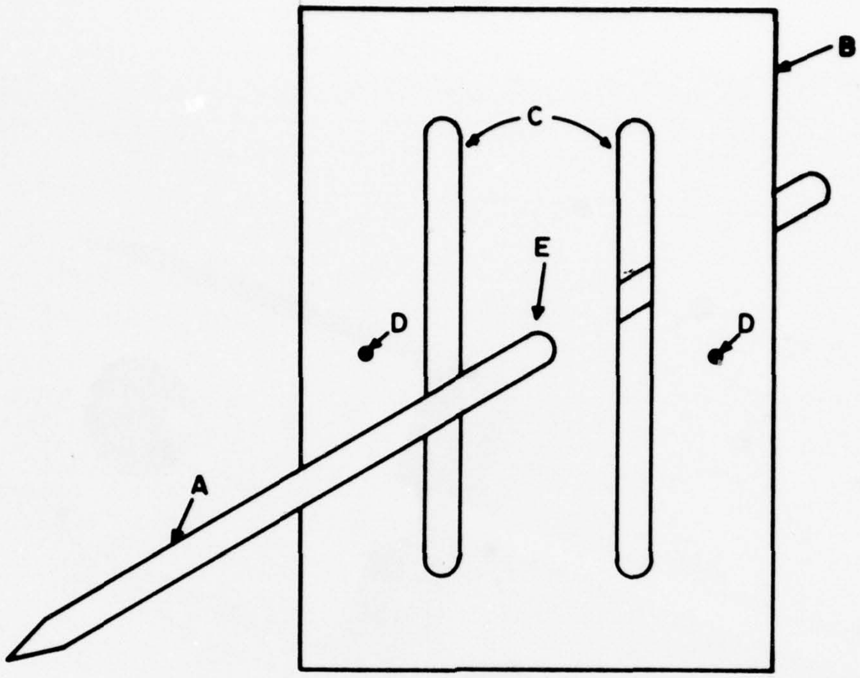

Figure 1. Needle and Pivot Point (NAPP) Mechanism.
A. Ceramic needle
B. Unidirectional sheet spring (stainless steel)
C. Slots in stainless steel sheet
D. Points of attachment to supporting structure (not shown)
E. Pivot point

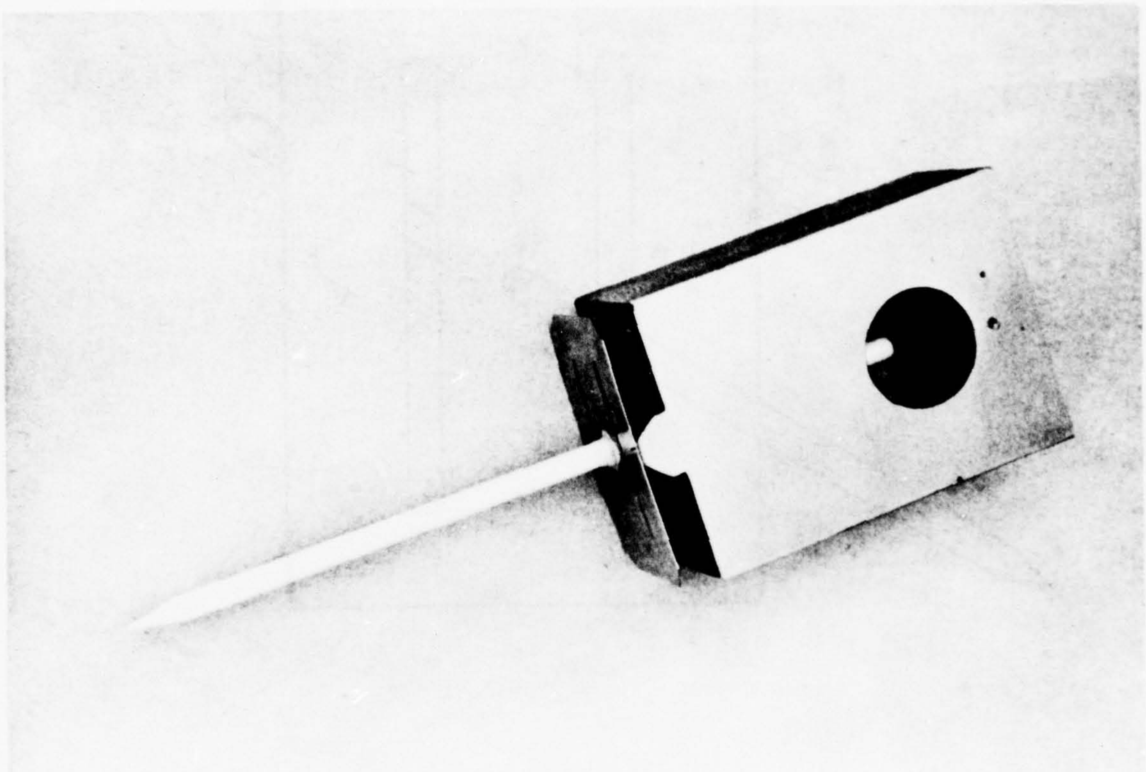

Figure 2. Model of the NAPP mechanism.

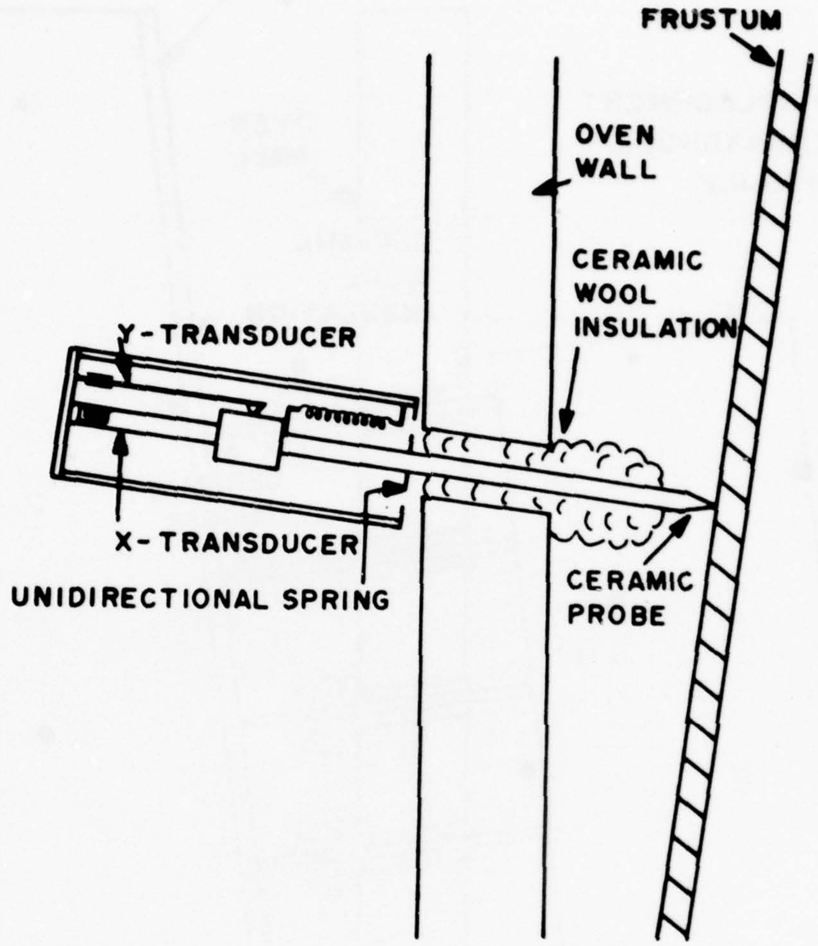

Figure 3. 3-D NAPP displacement transducer. The Z-transducer is not shown, but it may consist of strain gages mounted on the unidirectional spring.

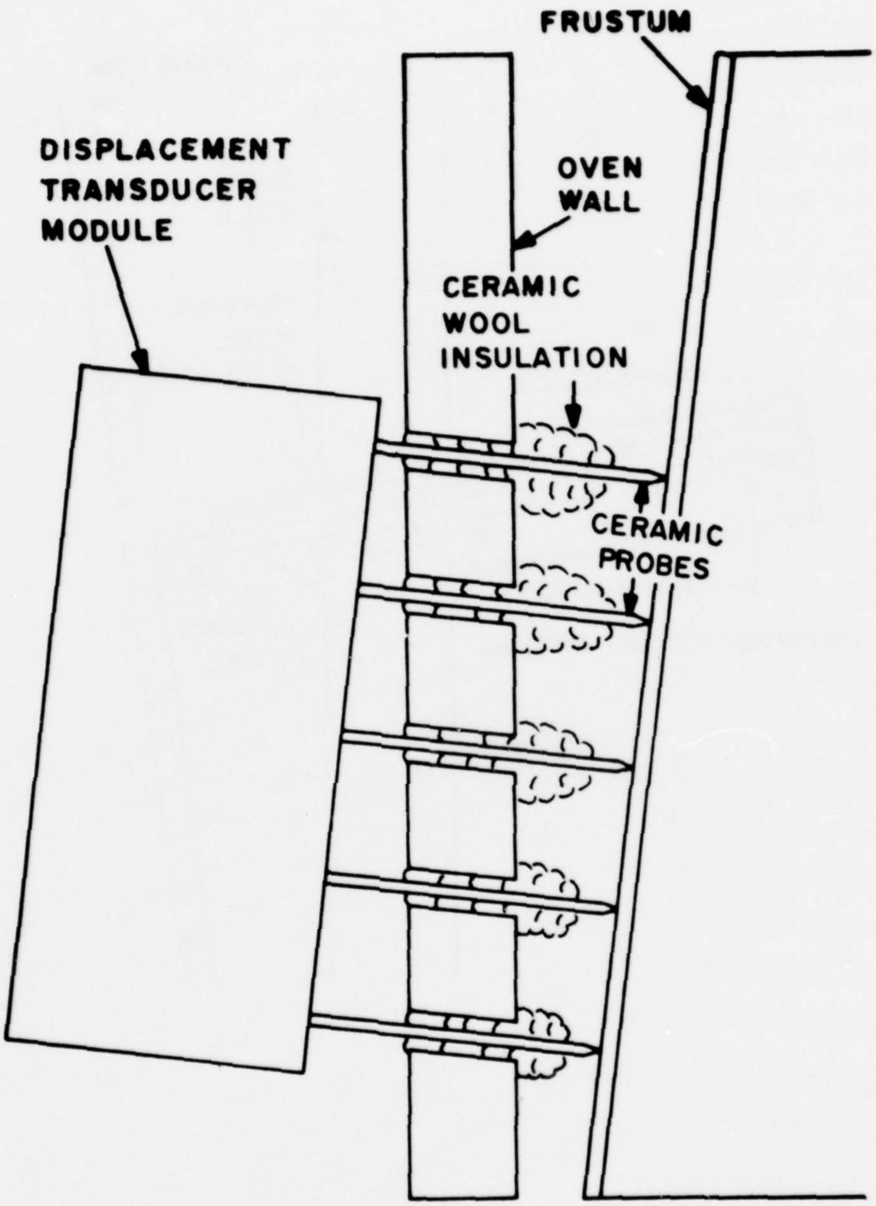

Figure 4. Multiple-point NAPP module.

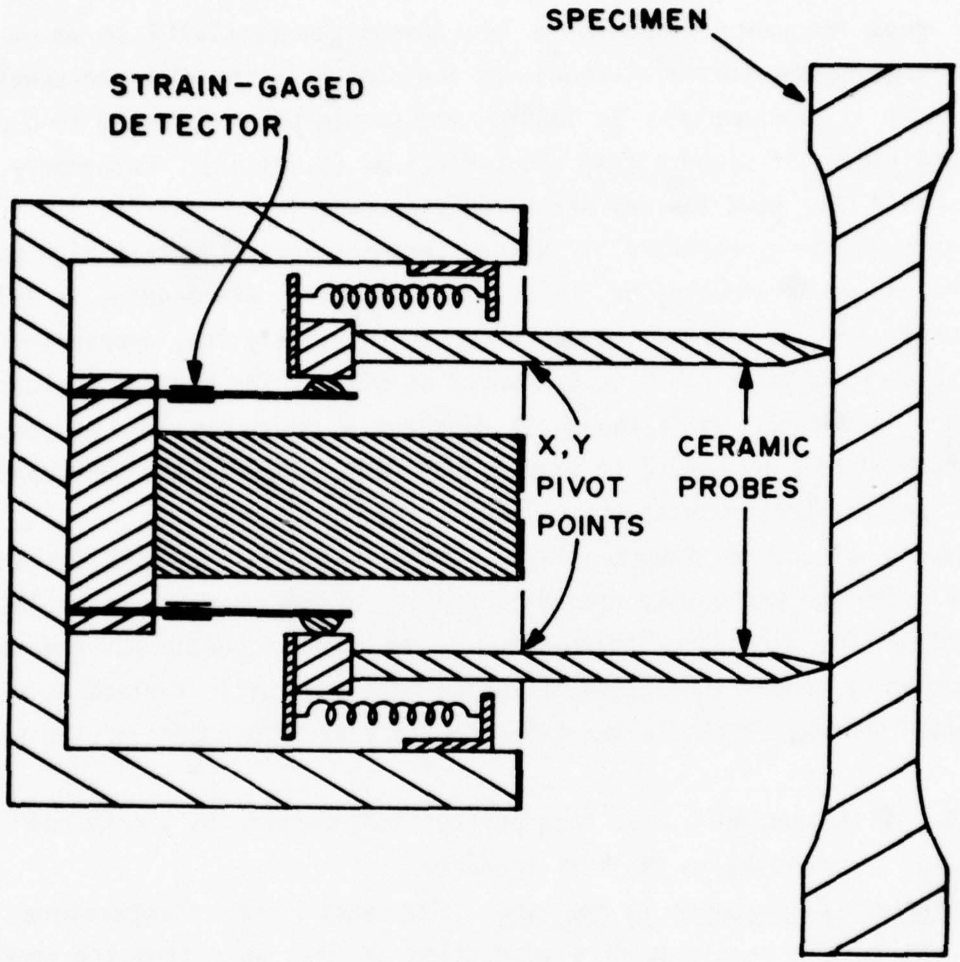

Figure 5. 1-D NAPP strain transducer.

Ceramic Needle Material: First, it had to be determined whether a suitable high-temperature ceramic material exists from which the needles for the NAPP transducers could be made. The needle material should have a high modulus for good frequency response, a low thermal conductivity so as not to create a large temperature disturbance at the contact point with the specimen, good strength at temperatures to 1650°C, and should be sharpenable to a point with an end radius of no more than about 0.025 mm (0.001 in). Futhermore, the ceramic should have good thermal shock resistance.

A study of the properties of various ceramics indicated that high-purity aluminum oxide would probably be the optimum material. Its modulus is 393 GPa (57×10^6 psi), and its thermal conductivity is relatively low, decreasing from 39.7 W/m·K at room temperature to 6.3 W/m·K at 800°C. The maximum no-load use temperature is 1900°C, and although it displays a creep behavior at temperatures above 1400°C, it should be useful for short times in the NAPP application for specimen temperatures up to 1650°C.

A sample of 3.2 mm diameter Al_2O_3 rod was obtained to test its sharpenability. The rod was easily ground to a point of radius 0.025 mm or less by the use of a fine diamond grinding wheel. The ceramic needle was then thermally shocked by suddenly pressing its point onto a metallic surface at 650°C. Several such thermal shocks failed to produce any visible damage to the needle point.

Thus, it is concluded that high-purity Al_2O_3 ceramic is a good candidate material for the needles in the NAPP transducers.

Temperature Disturbance in Specimen: The most severe temperature disturbance due to the needle-point's conduction of heat away from the specimen at the contact point would occur in the laboratory tensile test specimen which is electrical resistance-heated at up to 1100°C per sec. It was necessary to write a small special-purpose computer program to solve the transient heat-transfer problem and thus to determine the magnitude and extent of the temperature disturbance. A listing of the program, named THETA, is included as Appendix A. The program was written using the finite element approach. The contact area at the needle-point was assumed to be a circle 0.075 mm (0.003 in) in diameter. The needle-point cone angle was assumed to be 30°, and the temperature in bulk of the specimen material was assumed to rise linearly from room temperature to the maximum temperature for the specimen material (1100°C or 1650°C). The temperature variation of the thermal conductivity of the Al_2O_3 needle was included, but a constant thermal conductivity of the specimen material proved adequate.

The program calculated the temperature history both in the specimen and in the needle; the heat flow rate from the specimen into the needle was also computed. Computer runs were made for three different specimen materials: beryllium, Mar-M-200 (a 60 percent Ni alloy), and TZM (a Mo alloy containing Ti and Zr). The maximum temperatures for these materials were assumed to be 1100°C, 1100°C, and 1650°C, respectively, with a heating rate of 1100°C/sec in all cases.

Figures 6, 7, and 8 show magnified idealized drawings of the needle point contacting the specimen. For purposes of computation, the needle-point end is assumed to be flat. This is also conservative inasmuch as the heat flow into the needle would be more restricted by assuming a hemispherical end, for example. Figures 6, 7, and 8 also show the calculated temperature distributions in the specimen at the instant when the bulk of the specimen reaches the maximum temperature, at which time the temperature disturbance in the vicinity of the needle point is the most severe. The maximum temperature disturbance was 156°C in the Mar-M-200 material because of its relatively low thermal conductivity. However, Figure 7 shows that at a depth of only 0.1 mm (0.004 in) from the contact point, the temperature disturbance is less than 30°C, and at 0.25 mm(0.010 in) depth it is only 8°C. Figures 6 and 8 show that the temperature disturbances for Be and TZM are about one-third as large as for the Mar-M-200.

Considering the modest magnitudes of the temperature disturbances and considering the very small volume of specimen material involved, it was concluded that the disturbances will have a negligible effect on the stress-strain test results. The only possible exception might be in a tensile test to failure, where thermally-induced stresses at the needle contact points might contribute to premature failure at those points.

Frequency Response: Since it is desired to instrument strains up to 0.1 mm/mm at strain rates up to 10/sec, a particular test may last only 10 msec, which is the time to reach a strain of 0.1 at a strain rate of 10/sec. An adequate instrumentation system should therefore have a 10 to 90 percent rise-time of better than 1 msec, and hopefully it should be as short as 0.1 msec.

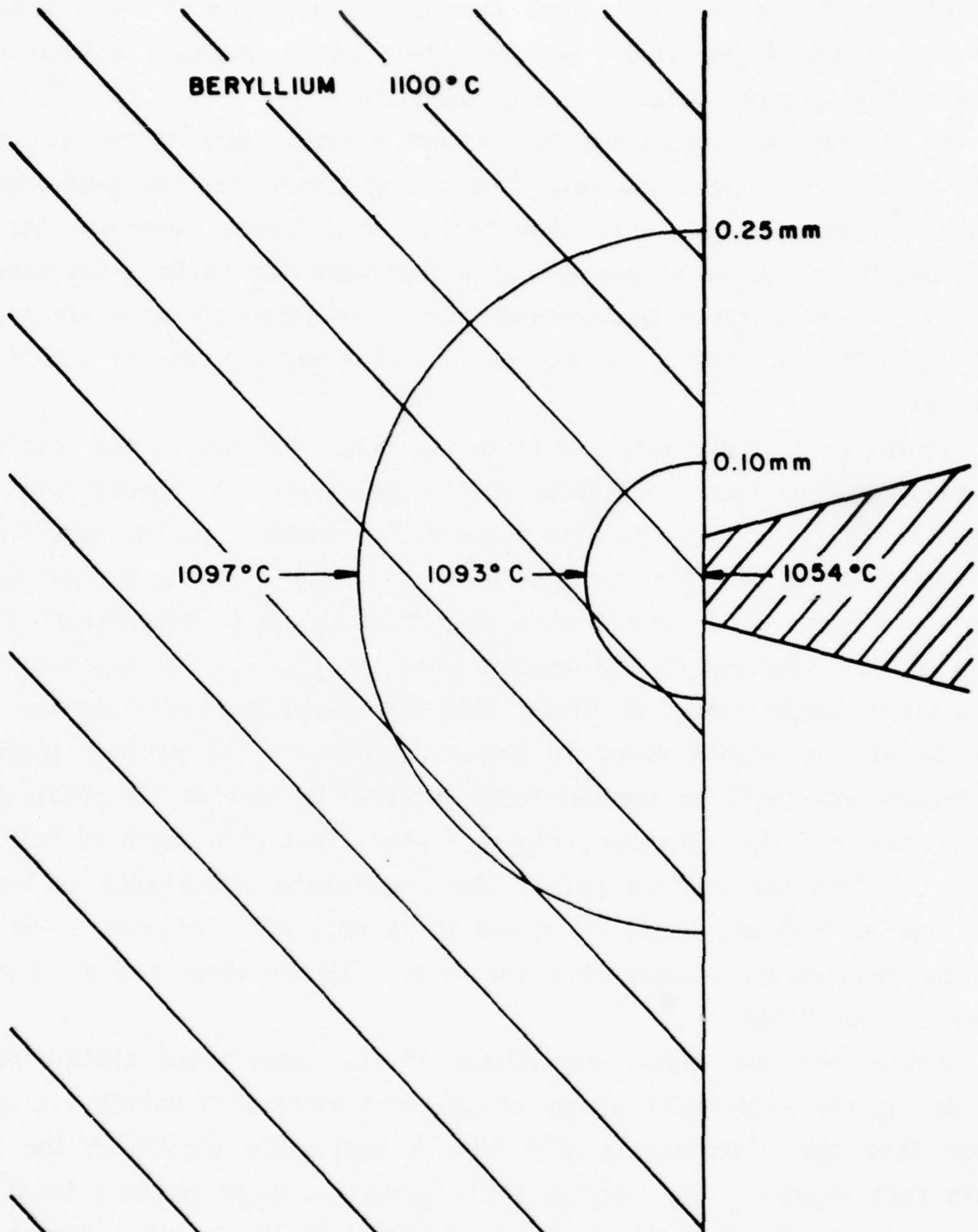

Figure 6. Temperature distribution around the needle contact point in a beryllium specimen after heating to 1100°C in 1 sec.

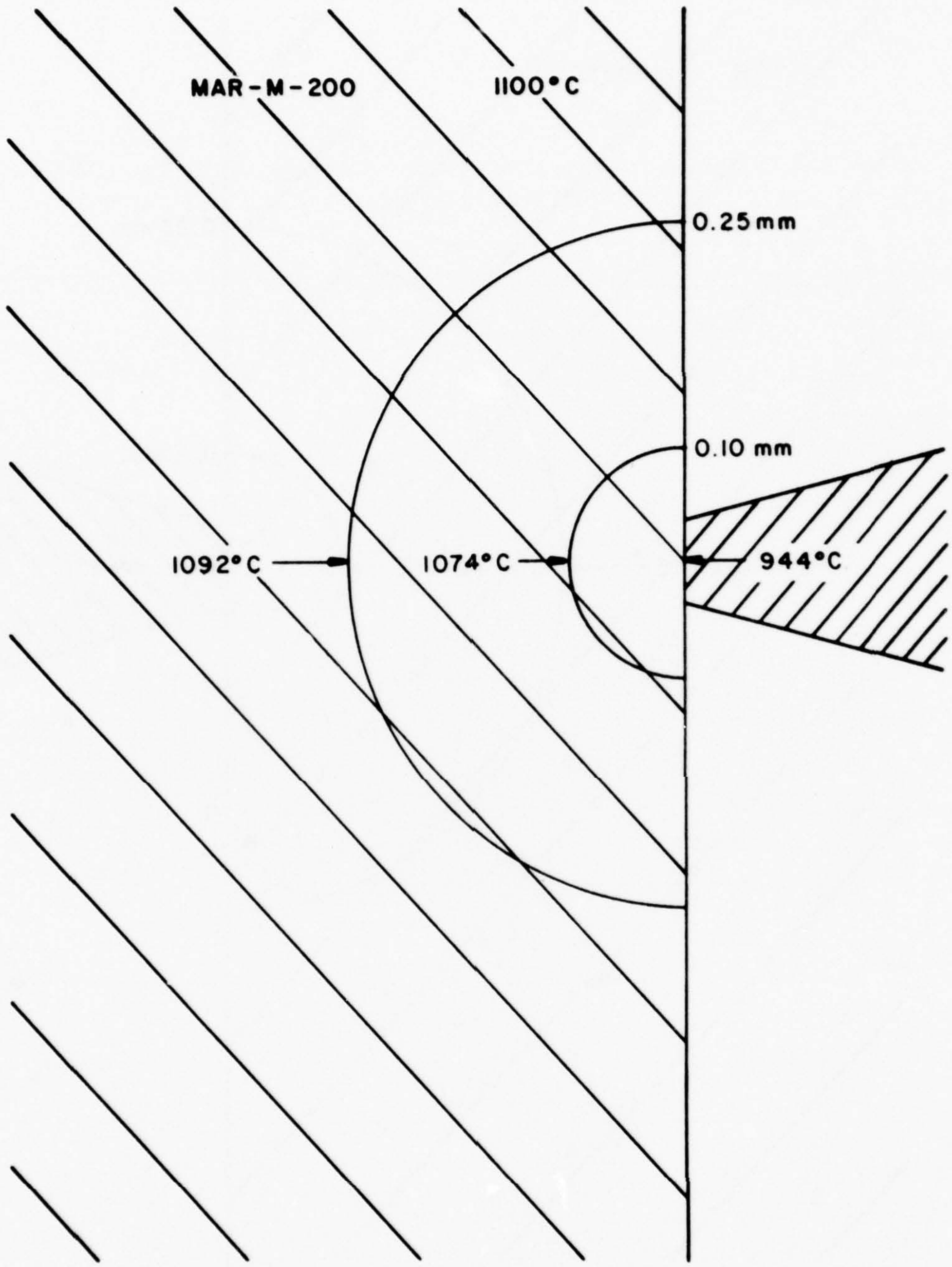

Figure 7. Temperature distribution around the needle contact point in a Mar-M-200 specimen after heating to 1100°C in 1 sec.

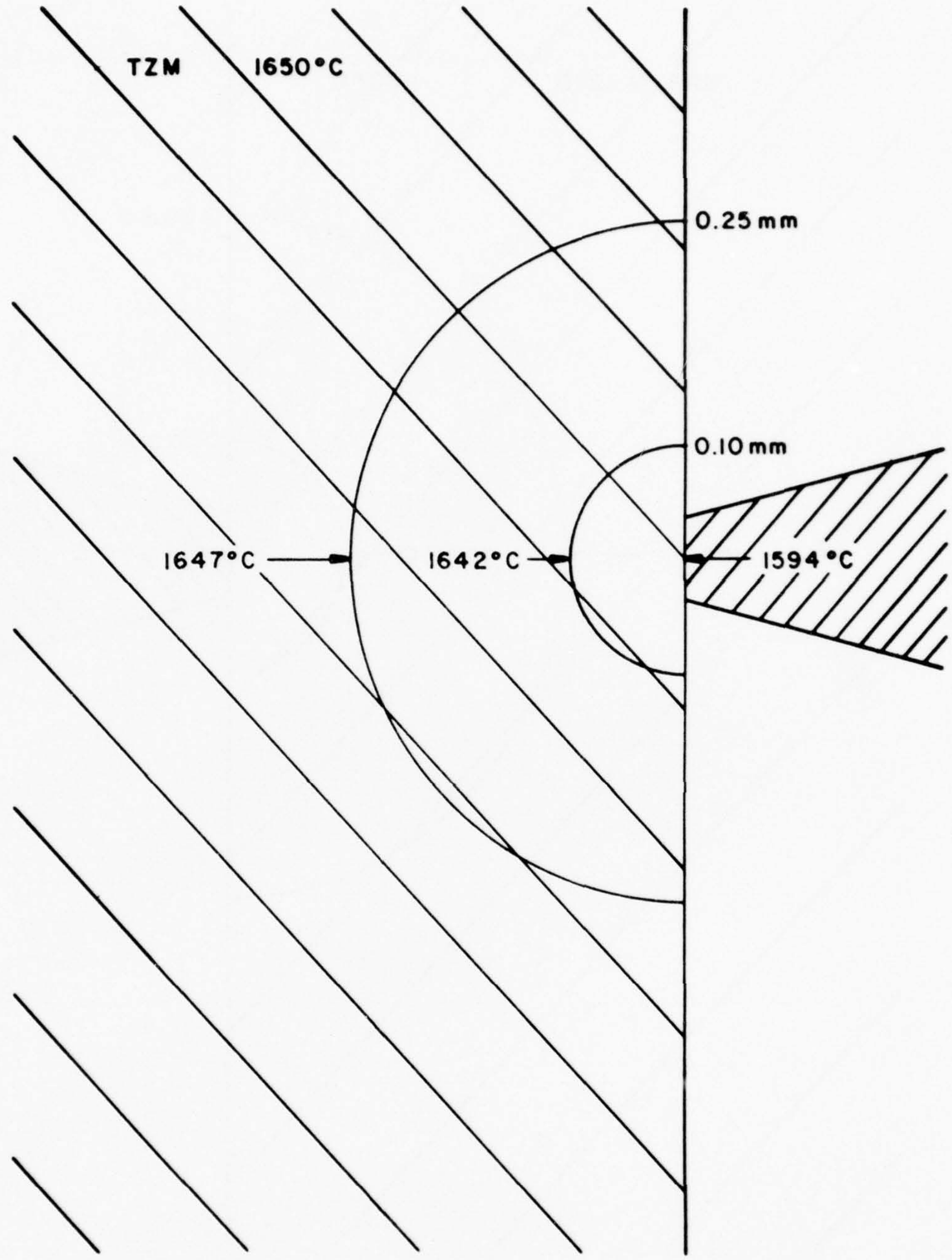

Figure 8. Temperature distribution around the needle contact point in a TZM specimen after heating to 1650°C in 1.5 sec.

It is anticipated that electrical resistance strain gage technology will be used to instrument the motion of the end of the ceramic needle in the NAPP transducer, as indicated in Figures 2 and 5. Rise-times of 0.1 msec are no problem for the electrical circuits associated with strain gages; thus, only the mechanical response of the system is of concern.

Since the strain-gaged arms which respond to the motion of the rear end of the needle can be made quite short compared to the length of the needle, it appears that the major contribution to the rise-time will come from the natural resonant vibration frequency of the needle itself. Therefore, the equation from Roark's Formulas for Stress and Strain, Fourth Edition, p. 369, for the natural frequency of a beam with supported ends was used to estimate the rise-time of the needle. The length from the pivot point to the needle point was taken as the length of the beam, and the rise-time was taken as one-third of the period. With these assumptions, and using the density and modulus of Al_2O_3 for the beam properties, the rise-time vs. needle length is shown in Figure 9 for several needle diameters. It appears from Figure 9 that a rise-time of less than 1 msec may be attainable with needle lengths up to about 200 mm (8 inch), but that a rise-time of 0.1 msec may be difficult to achieve even with needles as short as 100 mm from the sharp end to the pivot point.

The above calculations were made assuming a solid Al_2O_3 needle of circular cross section. Gains of 10 percent or more in rise-time can be achieved by using a hollow tube for most of the length of the needle. A 12 percent decrease in the rise-time was calculated for a given outer diameter as a result of changing from a solid rod to a tube with an inner diameter of half of the outer diameter. Also, the heat transfer along the length of the tube would be 25 percent less than in the rod, provided convection in the core of the tube could be prevented. A decrease of nearly 50 percent in rise-time could be attained by making the needle body of beryllium rather than Al_2O_3, but still using Al_2O_3 for the sharpened tip becuase of its good high-temperature strength and low thermal conductivity. The beryllium has a higher modulus-to-density ratio than Al_2O_3, which helps the frequency response, assuming an equivalent weight/length ratio. The beryllium has a much higher thermal conductivity, however, which may be a detriment because of heat conduction to the instrumented shank end of the needle. Also, it melts at about

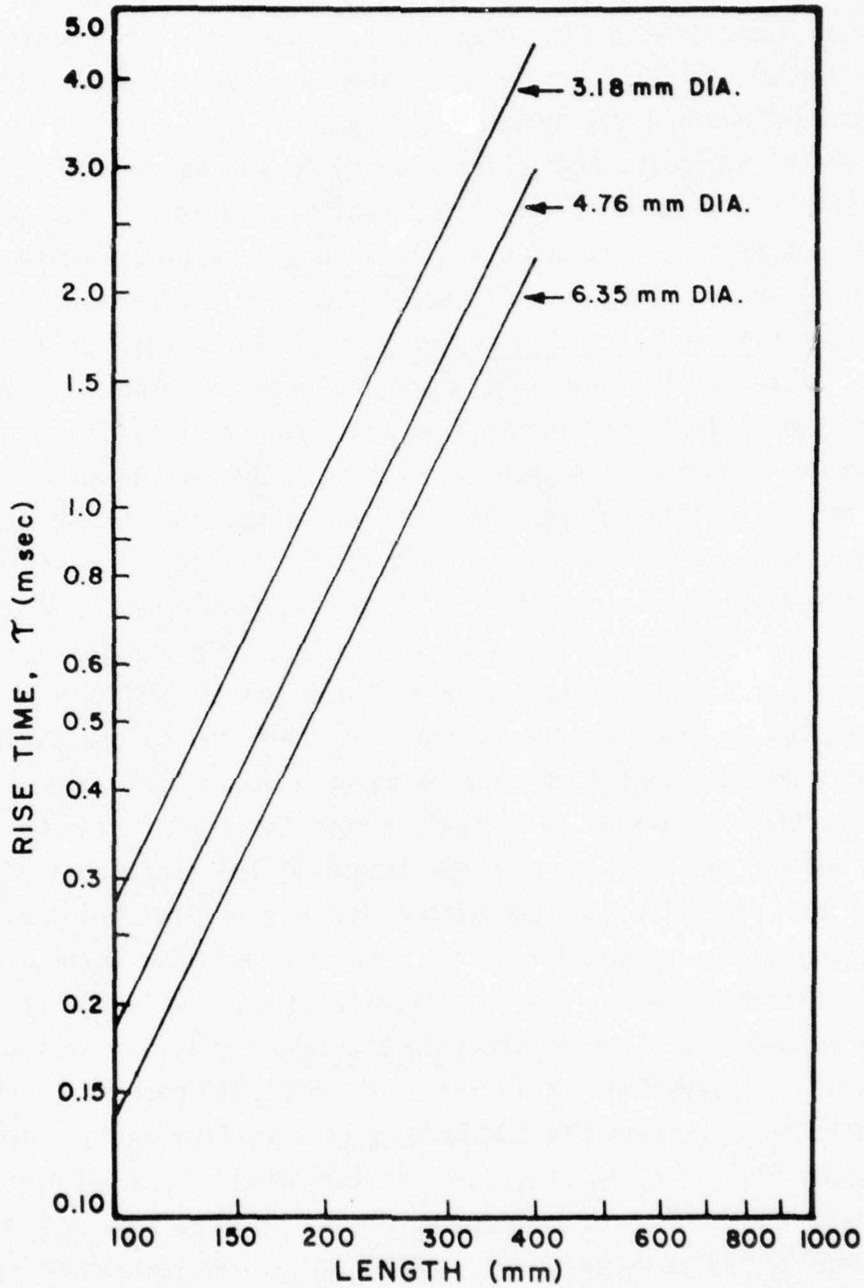

Figure 9. Signal rise time vs. length of the ceramic needle for three needle diameters.

1350°C, and therefore cannot be used at temperatures as high as those which can be tolerated by Al_2O_3.

To summarize, it appears that a frequency response of 1 msec or possibly substantially better should be attainable for the envisioned usage of the NAPP system.

Data Acquistion System: Thus far, the discussion has considered for the most part only the transducer device which could be used in a multiple array to monitor triaxial motion at 40 locations on a structure in a high-temperature test facility. However, because three channels of information (motion in the x, y, and z directions) come from each monitored location, a successful test would require essentially simultaneous collection of data from 120 information channels. Moreover, since the entire test may last only 10 msec, and since at least 100 data points may be desirable from each information channel over the duration of the test, the desired data collection rate will probably be at least 1.2×10^6 data readings per second, on the average.

The feasibility of constructing a suitable data acquisition system using primarily commercial hardware was discussed with several representatives of companies which supply the applicable hardware. The general feeling was that such a data acquisition system would not be trivial to construct, but that it is certainly within the state of the art. Very preliminary estimates of its cost were in the range of $40,000 to $100,000, including the computer to store and process the data.

Another potential problem concerning data acquisition arises from the very high 60 Hz AC electrical currents which are used for heating the laboratory specimens from room temperature to 1100°C in only 1 sec. The electrical noise pick-up in the strain gages of the NAPP transducer would seem at first to present a difficult problem. However, an electronics circuit called a "phase locked loop" signal conditioner promises to be of help. In essence, it allows the strain gage signals to be transmitted at a particular frequency other than the 60 Hz interference frequency, and strongly rejects any noise other than at the frequency of the strain gage signal. Phase locked loop circuits are available as integrated circuit devices.

The investigations of the predicted performance characteristics of the NAPP transducer have proved quite encouraging. The device promises to be rather inexpensive to make and to use, relative to some other high-temperature strain instrumentation methods, yet it appears to be the only practical method which can meet the desired specifications for instrumenting numerous points on structures in a high-temperatre furnace. Furthermore, no special technology is required to use the NAPP devices other than the electronics technology which is standard in any research laboratory. Although problems will undoubtedly be encountered in developing the technique, none which would seriously affect the feasibility of a system based on the NAPP concept have been foreseen at the present time.

SUMMARY AND CONCLUSIONS

A survey of the literature revealed a number of methods which have been used in the past to measure strains in specimens at high temperatures. However, none of the methods described a technique for obtaining biaxial surface strain plus the displacement perpendicular to the surface.

A new high-temperature strain instrumentation method was therefore devised to provide the desired simultaneous strains and displacement measurements. The technique involves a ceramic Needle And Pivot Point (NAPP) device which translates the motion of interest to a location outside of the furnace in which the actual test takes place, such that the motion can be measured by standard room-temperature techniques.

Several features of the system based on the NAPP device were investigated, including (1) the availability of a suitable ceramic needle material, (2) the magnitude and depth of the temperature disturbance in the specimen which would result from the needle-point contact, (3) the frequency response (rise-time) which can be expected for a NAPP system, and (4) the feasibility of a data acquisition system for 40 NAPP transducers used simultaneosuly to instrument a structure tested inside a furnace. All aspects of the calculated performance appear to be satisfactory. In addition, the instrumentation system based on the NAPP transducer would be economical to produce, and would involve only standard technology which is common to all research laboratories. It is therefore recommended that a development program be initiated to fabricate, test, and perfect the NAPP transducer in preparation for applying it in full-scale tests of structures at elevated temperatures.

APPENDIX A
THETA COMPUTER PROGRAM LISTING

The following pages are a listing of program THETA, a special-purpose finite-element computer program which was written to calculate the temperature disturbance in the vicinity of the ceramic needle contact point in NAPP-instrumented specimens.

R2/C

```
      PROGRAM THETA
C     TEMPERATURE IN *C*
      DIMENSION T(30),R(30),DT(30),HC(30),TS(30),RS(30),DTS(30)
     1,HCS(30),RCS(30)
      CALL ASSIGN(2,'THETA.OUT;1')
      WRITE(5,105)
105   FORMAT('0ENTER NE, CR, DR, TA, TMX'$)
      READ(5,99)NE,CR,DR,TA,TMX
99    FORMAT(I4,4F12.3)
      WRITE(5,107)
107   FORMAT('0ENTER NES, DRS, RHS, CPS, CS')
      READ(5,99)NES,DRS,RHS,CPS,CS
      WRITE(5,106)
106   FORMAT('0ENTER DTM, DTP, RH, TSTOP ='$)
      READ(5,98)DTM,DTP,RH,TSTOP
98    FORMAT(4F10.0)
      TM=0.
      TSZ=20.
      CP=.25
      SL=1111.
      A=-1.327
      B=11.104
        IF(NE.GT.29)GO TO 26
      IF(NES.GT.28)GO TO 26
      TP=0.
      J=NE+1
      WRITE(2,101)NES,DRS,RHS,CPS,CS
101   FORMAT(15X,'PROGRAM THETA',///,7X,'NES',7X,'DRS',7X,'RHS',7X,
     1'CPS',8X,'CS',/,1X,I9,4F10.3)
      WRITE(2,108)NE,DR,RH,CP,TMX
108   FORMAT(/,8X,'NE',8X,'DR',8X,'RH',8X,'CP',7X,'TMX',/,1X,I9,
     14F10.3)
      WRITE(2,109)CR,TA,DTM,DTP,TSTOP
109   FORMAT(/,8X,'CR',8X,'TA',7X,'DTM',7X,'DTP',5X,'TSTOP',/,1X,
     1F9.4,F10.1,3F10.4,/)
      TA=TA/57.296
      CP=CP*4.187
      ST=.5-.5*COS(.5*TA)
      CPS=CPS*4.187
      RZ=CR*COS(.5*TA)/SIN(.5*TA)
      R(1)=RZ
      DO 1 I=2,J
      T(I)=20.
      R(I)=RZ+(I-1.)*DR
1     HC(I)=.0041888*RH*CP*(R(I)**3-R(I-1)**3)*ST
      DO 45 I=2,J
      RP = (R(I)+.5*DR)*CR/RZ
      IF(RP.LT.0.794)GO TO 45
      HC(1)=.00198*RH*CP*DR
45    CONTINUE
      DO 21 I=2,J
21    R(I)=RZ+(I-1.5)*DR
      STS=.5
      RS(1)=0.
```

```
0053          RS(2)=CR
0054          DO 31 I=3,NES+2
0055    31    RS(I)=RS(2)+(I-2.)*DRS
0056          DO 32 I=1,NES+1
0057    32    HCS(I)=.00419*RHS*CPS*(RS(I+1)**3-RS(I)**3)*STS
0058          RCS(1)=212.2/(CR*CS)
0059          RCS(2)=79.58*(1./CR-1./(CR+.5*DRS))/(CS*STS)
0060          RCS(1)=RCS(1)+RCS(2)
0061          DO 33 I=1,NES
0062          TS(I)=20.
0063    33    RS(I)=CR+(I-.5)*DRS
0064          HCS(1)=HCS(1)+HCS(2)
0065          DO 34 I=2,NES
0066          HCS(I)=HCS(I+1)
0067    34    RCS(I)=79.58*(1./RS(I-1)-1./RS(I))/(CS*STS)
0068          DTEMP=SL*DTM
0069          TI=20.
0070    9     TM=TM+DTM
0071          N=1
0072          DTMX=TMX-TS(NES)
0073          TAD=DTEMP
0074          IF(DTMX.LT.TAD)TAD=DTMX
0076          DO 36 I=1,NES
0077    36    TS(I)=TS(I)+TAD
0078          T(1)=TI
0079    25    QN=0.
0080          IF(N.EQ.J)GO TO 24
0082          TAV=.5*(T(N+1)+T(N))
0083          C=EXP(A*ALOG(TAV+273.)+B)
0084          RP=(R(N)+.5*DR)*CR/RZ
0085          IF(RP.GT.0.794) GO TO 43
0087    44    RC=79.58*(1./R(N)-1./R(N+1))/(C*ST)
0088          IF(N.EQ.1)GO TO 35
0090          QN=(T(N)-T(N+1))/RC
0091    24    DT(N)=(QL-QN)*DTM/HC(N)
0092    22    QL=QN
0093          IF(N.EQ.J)GO TO 40
0095          N=N+1
0096          GO TO 25
0097    35    QN=(TS(1)-T(2))/(RC+RCS(1))
0098          RCZ=RC
0099          QZ=QN
0100          GO TO 22
0101    43    CR = 318./(C*DR)
0102          GO TO 44
0103    40    QL=QZ
0104          M=1
0105    39    QN=0.
0106          IF(M.EQ.NES)GO TO 38
0108          QN=(TS(M+1)-TS(M))/RCS(M+1)
0109    38    DTS(M)=(QN-QL)*DTM/HCS(M)
0110          M=M+1
0111          QL=QN
0112          IF(M.LE.NES)GO TO 39
```

```
0114            DO 8 I=2,J
0115    8       T(I)=T(I)+DT(I)
0116            DO 41 I=1,NES
0117    41      TS(I)=TS(I)+DTS(I)
0118            TI=T(2)+(TS(1)-T(2))*RCZ/(RCZ+RCS(1))
0119    6       IF(TM.LT.TP)GO TO 5
0121            WRITE(2,10)TM,QZ
0122    10      FORMAT(///,1X,'TIME',F7.3,10X,'HEAT FLOW',F9.2,' WATTS',//,2X,
               1'N',12X,'R',10X,'TEMP',/)
0123            DO 11 I=1,J
0124    11      WRITE(2,12)I,R(I),T(I)
0125            DO 42 I=1,NES
0126     42     WRITE(2,12)I,RS(I),TS(I)
0127            TP=TP+DTP
0128    5       IF(TM.GT.TSTOP)GO TO 7
0130            GO TO 9
0131    26      WRITE(5,27)
0132    27      FORMAT('ONE OR NES IS TOO LARGE')
0133    12      FORMAT(1X,I3,F13.3,F14.2)
0134    7       CALL SPOOL(2,XYZ)
0135            STOP
0136            END
```

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